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Simulating Human Characteristics for Operational Studies

Ian V. Lloyd

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ABSTRACT

The effect of errors in models of human response on the outcome of a simulated sequence of events can be significantly large compared to the precision with which physical events are typically modelled. The effects of such errors can accumulate when events are propagated up and down a command and control chain. For a simulation of a system to be realistic, the products of simulated human decisions should be available in accordance with human cognitive limitations and at human rates of response.

An approach to structuring simulations of human tactical response is proposed. This approach requires pre-processing of the simulation procedures to establish their cognitive resource loading for different levels of simulated expertise. Run-time processes are also required to regulate access of behaviour algorithms to simulated cognitive resources, and to dynamically adjust those resources as a function of stress.

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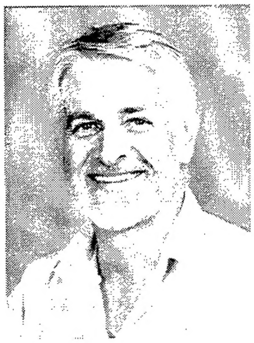
Executive Summary

Physical characteristics of system components are not by themselves sufficient to describe the performance of military systems unless they are totally automated. Analysts have traditionally paid considerable attention to fidelity when modelling physical entities and processes but have been more offhand when modelling the human component. Military systems typically involve human decision makers connected in a command and control (C2) structure. The effect of even small errors in human response on the outcome of a sequence of events can be large. The cumulative effect of errors in human response time, if propagated up and down in a C2 system can be significantly large compared to the precision with which physical entities are modelled.

Timing is an important issue in the simulation of human responses. The results of a simulated human decision, including any intermediate results, should be produced in accordance with human rates of response and should be subject to typical human characteristics. There is a need to simulate the cadence of human response, not just the end result. Although many aspects of human performance are the subject of continuing research, incorporation of the effects of human characteristics, including the effects of stress, should be provided for in the structure of any model of human tactical response. A response model should at least make provision for the future inclusion and refinement of a human performance model.

An approach to structuring simulations of human tactical response is proposed, based on the literature in human cognition. The structure allows for the simulation of individual differences in human performance, different levels of expertise and the effect of stress. This approach requires pre-processing of the simulation procedures to establish their cognitive resource loading for various levels of simulated expertise. Run-time processes are also proposed to regulate access of behaviour algorithms to simulated cognitive resources, and to dynamically adjust those resources as a function of stress.

Author



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Contents

1. Introduction

The appeal of simulation as a tool for operations analysts is that it is possible to construct elaborate representations of systems that are either real, imaginary or proposed and to conduct experiments on them. Traditional analytical methods can be inadequate if the complexity of the system being modelled increases beyond a fairly basic level. This generally means that studies based on analytical models of complex systems are often limited by the simplifying assumptions required to obtain any sort of solution. In contrast, the fidelity of a simulation is limited only by the domain knowledge of the analysts, provided that the formalism used is sufficiently expressive. The utility of any simulation is, of course, also limited by the computer processing power available.

Military systems typically involve human decision makers connected in a command and control (C2) structure. It has long been recognised that physical characteristics of system components, such as range, speed, endurance, coverage, lethality etc., while forming a necessary basis, are not by themselves sufficient to describe the performance of a real system. A real system, unless it is totally automated, includes human decision makers and human-to-human communications.

One approach to the simulation of such systems is to conduct hybrid studies in which the physical entities are simulated but the decisions are referred to operators. This is done in war gaming simulations. There are two main problems with this for operations analysis: (1) The number of human players in even the smallest military setting can run into the hundreds. It would be necessary to provide a complete set of trained human 'players' to run a simulation at anything near real-time speed. It would be difficult to run much faster. The use of statistically-based methods, typically involving thousands of runs, to obtain statistical results, is clearly impractical. (2) The results of simulations involving real humans are not generally repeatable if the decisions being made are not trivial. Consistency and repeatability are necessary for operational effectiveness studies seeking to establish the causal relationships between system parameter settings and system performance. The effect of human decisions can dominate the effect of system physical parameters. If the experiment is to evaluate the effect of a change in a system parameter, the effect of an unrepeatable human input can render the results meaningless. It is clear that simulated 'human' decision making is desired, for both speed and consistency.

Analysts have traditionally paid considerable attention to fidelity when modelling physical entities and processes but have been more offhand when modelling the human component. This may be, in part, due to the predominantly engineering and computer science background of those designing and building the simulations. It may be due to discomfort with the generally less precise, equivocal, incomplete and often contentious nature of theories of human behaviour available in the literature. Whatever the reason, it is important that some attention be applied to rectifying the problem. The effect of even small errors in human response on the outcome of a

simulated sequence of events can be large. The cumulative effect of errors in human response time, if propagated up and down in a C3 system can be significantly large compared to the precision with which physical entities are modelled. As a hypothetical example, an aircraft may be detected by an air defence radar. It may be necessary to compare its position, direction, speed, altitude and other information with comparable information about known friendly and neutral aircraft in the area, obtained from several different sources. It may be necessary to compare these data and infer the likely intention of the target which would then be relayed to the air defence commander. The commander would have to make inferences in a wider context and consider the likely developments of the situation, including the deployment of friendly forces and potential consequences. His decision would be promulgated through several stages of operational and tactical control to the point of response. An error of several minutes in an estimate of the total time taken for this sequence of events would not be unreasonable. A jet fighter can move about 15 nautical miles in a minute at supersonic speed; 10 miles a minute near ground level. In several minutes, the tactical situation (which might be modelled at a resolution of a millisecond) could change markedly.

This paper seeks to establish a basis for the future incorporation of realistic human characteristics in simulated human 'players'.

Issues addressed are:

- The characteristics required of a human tactical response model for operations analysis studies.
- The structure of a simulation of tactical response, including preferred formalisms.
- Human cognitive limitations.
- A proposed architecture for incorporation of human limitations in tactical response simulations.

2. Human Tactical Response

2.1 Requirements for a Model

Timing is an important issue in the simulation of human responses. The results of a simulated human decision, including any intermediate results, should be forthcoming in accordance with human rates of response and should be subject to typical human biases. There is a need to simulate the human response *process* with a finer granularity, not just the end result. The effect of stress on the responses should be realistic. Although many aspects of human performance are the subject of continuing research, incorporation of the effects of human limitations should be provided for in the structure of any model of human tactical response. A response model should at least contain 'hooks' for the future inclusion and refinement of a human performance model.

The level of detail in any component of a model will depend on the relative importance of that component to the role of the human being simulated. For example, a fighter pilot model will require a more detailed sensory processing component than an air defence commander. The fighter pilot is performing a role analogous to that of a football or tennis player. Visual and auditory processing is significant and, although forward tactical projection is required, the externally imposed requirement for immediate action limits the possibilities for deep reasoning. At the other end of the scale is the commander making strategic decisions, for whom sensory processing is much less important. The commander's role is analogous to that of a chess player. Any decision can have significant consequences for the whole game. There is a time pressure, but the tempo of decision making is quite different to that of a fighter pilot, for whom any decision, made quickly, could be better than none. For the commander, a good decision, made slowly is much more desirable than a poor decision made in haste. The nature of the decision making process is likely to be quite different.

Not all humans have the same level of experience or skill. There is a need to be able to set the model so that it will provide a response typical of humans with various levels of expertise.

It is not anticipated that this simulation of human reasoning will be required to evaluate the effectiveness of its own responses, devise improvements and learn. A truly 'intelligent' simulator would, over time, change its response to a given situation as a result of 'experience'. Repeatability is an important requirement for a simulator to be used in operations research; the requirement is for 'canned' human decision making. Development of the tactical knowledge base will be an activity separate from the running of the simulation.

2.2 Simulation of Tactical Response

A top-level description of human behaviour in a tactical setting should include the processes involved in developing situation awareness, making decisions, then acting in accordance with a set of goals. Almost any discussion of military doctrine now includes the 'OODA loop' - Observe, Orient, Decide and Act (attributed to US Air Force pilot John Boyd). The importance of the OODA loop is held to be (eg. Westwood 1996) that, in a adversarial situation which is changing in response to, and in reaction to, the decision maker's actions, the tactical advantage lies with the side with the faster and more accurate loop cycle.

The stages: 'Observe' and 'Orient' can be equated to perceiving and building situation awareness (SA). Situation awareness has been divided (Endsley 1989, Endsley & Bolstad 1993) into three levels. At Level 1 the individual perceives the information. At Level 2 the individual comprehends the meaning of the perceived data and, at Level 3, projects that comprehension into an expected future situation.

Gledhill and Goss (1995) provide a sequential list, shown in Figure 1 below, of phases in air combat. These are sufficiently general to serve as a model for tactical decision making in a wider context.

a) Detection

b) Classification

c) Recognition/Identification

d) Inference of Intention

e) Threat Assessment

f) Generate Tactical Options

g) Evaluate and Select Options

h) Execute Options

i) Monitor and Evaluate Effectiveness

j) Iterate on (a-i).

Figure 1. Phases in Tactical Response

Detection can be direct visual (or even auditory) contact, but targets are more commonly sensed remotely by radar or other electronic means and the information is shared over the C3 net by data link. Information about the target is seen by the human operator on a computer screen or is relayed in a spoken message.

Classification is here taken to mean the assignment of the detected to a class; a missile, aeroplane or ship, for example. This may be followed by **recognition/ Identification,** where the object is more specifically categorised into a particular type, eg. F/A-18.

Inference of Intention may be trivial with friendly targets with Identification Friend or Foe (IFF) equipment or participants on the same data link net but it may be highly speculative for non-cooperative targets. **Threat Assessment** adds inference of threat capability to inferred intention to arrive at an estimate of the potential of the target to do harm. Note that the phases from classification to threat assessment are not necessarily as clear-cut as presented here. The process called 'evaluation' In some military communities would cover these phases. The terms 'classification' and

'identification' can be contentious. 'Classification' can be used as a noun and refer to the class and intent of the target, eg. 'air target - hostile'. 'Identification' can be very specific, eg. the actual hull number of a ship.

Generate Tactical Options is the first part of the process of making a decision and responding. **Evaluating and selecting** these options is the next, followed by **execution, monitoring and evaluating** the selected plan of action.

Tactical decision making does not necessarily adhere to this structure. Humans, particularly experts, make use of a rich framework of context and cues to recognise a situation[1] and decide on a response without comparing options. This process is known as a Recognition Primed Decision (RPD)[2]. The factors contributing to a RPD are goals that make sense so that 'foolish' responses are not considered, selectivity in only using relevant cues, expectations that accurately reflect the unique features of a situation and knowledge of appropriate responses. A familiar situation might be recognised and responded to almost automatically without much conscious effort, while an unfamiliar situation could require the generation and evaluation of multiple options in line with the sequence of phases described above[3].

Whatever the structure of the decision strategy, each one of the phases in Figure 1 is definitely an aspect of tactical response and so represents a process that must be simulated. A variety of methods have been used to simulate these processes. Gledhill and Goss (1995) have surveyed and assessed the strengths and deficiencies of various formalisms used. Figure 2 has been adapted from that paper.

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[1] Situated cognition claims that knowledge is context-dependent. The way a situation is perceived and decisions are made about it depend strongly on the situation, ie. The processes are not independent of the data they are processing. See Menzies (1996) for a discussion of the challenge presented to Artificial Intelligence by situated cognition.

[2] An influential view of the factors contributing to the recognition-decision process is available from Klein (1993) and the Naturalistic Decision Making (NDM) school.

[3] See the section on Decision Making in Appendix 1.

PHASE	FIELD	METHODS			FORMALISM
Detection		Reasoning about time			subsymbolic, symbolic
		Reasoning about space	Reasoning under uncertainty	Mapping from primitive data to higher order abstractions	subsymbolic, symbolic
Classification	Data Fusion	Assignment of Class membership			subsymbolic, symbolic
Recognition/ Identification		Reasoning about Identity	Reasoning under noise		agent
		Reasoning about Team Membership			
Inference of Intention		Reasoning about Intentionality	Reasoning under incomplete information		agent
		Reasoning about Joint Intentionality			agent
Threat Assessment	Situation Awareness	Reasoning about Intentionality Reasoning about Joint Intentionality	Reasoning with conflicting information		agent
Generate Tactical Options		Reasoning about Plans			agent, symbolic
Evaluate and Select Options		Reasoning about Joint Plans			
Execute Options	Tactics selection		Reasoning about Beliefs/ Percepts	Mapping from higher order abstractions to primitive data (action requests)	
Monitor and Evaluate Effectiveness					

Figure 2. Tactical Response Model Methods

Subsymbolic formalisms are essentially numerical (eg. bearing and distance), while symbolic formalisms are qualitative, or comparative (eg. 'fast', 'in front of', 'threatening'). An agent is a computational procedure that has data, or *beliefs*, about the real world, goals, or *desires*, plans for achieving goals and *intentions*; activated plans in the process of being carried out, or currently suspended. Gledhill and Goss (1995) conclude that this *beliefs, desires, intentions* (BDI) formalism (Georgeff 1991 and references therein) has the most expressive power for the simulation of human tactical behaviour and is the basis of the agent-oriented SWARMM model and its successors. Considerable research effort has been applied to acquiring a capability for Air Operations Division (AOD) in the use of Artificial Intelligence (AI) techniques for a variety of aviation applications (Goss & Murray 1996) and for operational analysis of air combat in particular, using the agent-oriented 'SWARMM' model (Lucas *et al* 1992, Tidhar *et al.* 1995, Appla & Steuart). This work is being extended, in 'SWARMM++' (Appla *et al.*) and dSWARMM (Busetta *et al.* 1996), which will be used for future Airborne Early Warning & Control (AEW&C) studies. These developments are intended to accommodate larger systems with a command, control and communications (C3) structure. The human reasoning in these simulations is written in the dMARS™ language (AAII 1995) which implements plans of behaviour contained in tactical libraries using the BDI formalism. It is important for the fidelity of these large-scale simulations that the development of new agents takes human characteristics into account.

It is not the aim of this paper to propose an alternative set of reasoning processes to the ones already in use. Their effectiveness in generating a satisfactory response to each situation is outside the scope of this discussion. They may, however, arrive at optimised solutions in a time that no human could possibly replicate. The proposal is that, whatever processes are being used, the overall structure of the simulation should take human limitations into account.

3. Human Cognitive Limitations

Human cognition is discussed in some detail in Appendix 1. The important features are summarised below.

The first stage of cognition, in a tactical context, is perception, which, in a familiar environment, is a largely automatic process based on stored patterns in memory[4] and does not generally use cognitive resources.

[4] Schemata are collections of patterns or templates of knowledge derived from past experience. They provide the guidance for the recognition of images.

Working memory can be regarded as the temporary registers, or scratch-pad of the general memory system[5]. The total effective capacity of working memory is about seven items (+/-2). This capacity is decreased by stress. The amount of information in each of item, or 'chunk' in working memory is variable. Chunks are groupings of associated information[6]. The limited number of items that can be held in working memory can be regarded as being pointers to chunks in long-term memory. The more information in each chunk, the more information effectively available in working memory.

Long-term memory contains most of the stored information. It is believed to be permanent and have an effectively infinite capacity[7]. Long-term memory contains all of our experience of, and beliefs about the World. It is the basis of expertise, which depends upon a framework of automatic pattern matching. Experts are able to manipulate a lot of information in working memory because each chunk refers to a deep structure of semantic content in long-term memory. They are more likely than novices to be able to recognise a situation and generate an appropriate response by pattern matching with information stored in their long-term semantic memory. The expert can call upon larger, more appropriately structured 'chunks' of information with which to match the currently perceived situation. The expert is more likely to be able to make a decision with minimum use of working memory and attention, while the novice will have to use both of these resources to make sense of the situation and generate a response.

Automatic processes, based on familiar patterns in long term memory, are fast and require no attentional resources. Attention can be focussed by conscious intent and also according to subconscious patterns of belief. Expectations contribute to perceptual focus by providing context. Comprehension of a situation can be based on automatic recognition if the situation is familiar. The less familiar the situation, the more attention and working memory resources are required to understand it.

'Attention' corresponds to the function of a cognitive processor. The number and complexity of cognitive tasks which can be done simultaneously is determined by the total attentional capacity[8]. Automatic tasks do not require attention and are performed

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[5] Note that any categorisation of memory is likely to be contentious. Although it is convenient to describe certain characteristics as belonging to different types of memory, the reality is always more complex.

[6] A chunk can be regarded as a 'set of adjacent stimulus units that are closely tied together by associations in the subject's long-term memory' (Wickens 1992). Chunking can be cumulative; chunks can be structured groupings of chunks.

[7] The major cause of forgetting from long-term memory is generally believed to be a failure in retrieval.

[8] The expressions: 'attentional resources', 'attentional capacity', 'cognitive workload' and 'mental workload' are often used in the literature in contexts that suggest that they mean the same thing. Ellis & Hunt (1993) provide some clarification in a discussion of capacity models of attention: '...we have a certain amount of cognitive capacity to devote to the various tasks confronting us. Different tasks require different amounts of this capacity, and the number of

without conscious awareness, although there is conscious awareness of the product. Stress tends to narrow attentional focus.

A severely time-critical role, such as a fighter pilot would involve an absolute minimum of evaluation of options by mental rehearsal. A commander, on the other hand, is much more likely to attempt to optimise a response by evaluating alternative courses of action. The availability of staff advice and computer-based decision-support aids will further complicate the model.

More complex situations require a deeper level of processing than pattern-matching. Manipulation of the contents of the knowledge base at a semantic level, and re-casting of the situation is required. Comparison and evaluation of options is required. Human biases in perception and assessment should be taken into account when modelling these processes[9].

An action can be as simple as changing a belief which, if held in working memory, is instantaneous. It can be a complex sequence of moves which have to be monitored in progress and continually re-evaluated in a changing environment. In this case, the intended action becomes part of the context of the situation assessments in the future.

4. Regulation of Cognitive processes in a Simulation

Where the process is not automatic, limited cognitive resources are used. The rate and effectiveness of 'thinking' about a problem depends on these factors, and the level of ability and experience of the thinker. Any simulation of human cognition should include a mechanism to regulate access to resources.

The tactical response processes outlined in Figure 1 are shown in diagrammatic form in Figure 3. Some postulated products (and sources) of these processes are also shown[10]. Percepts are the direct products of perception. Interpretations are the result of higher levels of recognition and understanding. Percepts and interpretations correspond to 'beliefs' in the BDI formalism. Intentions are the plans that have been decided upon and action is the result of those intentions.

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activities which can be done simultaneously is determined by the capacity each requires. If a single task demands intense concentration, no capacity will remain for an additional task. Within this approach, *attention is the process of allocating the resources or capacity to various inputs.'*

[9] Although it is reasonable to expect that experience makes an expert more likely than a novice to be able to make an immediate decision, and get it right, the assumption is not always valid. Experts are subject to biases and use of invalid heuristics.

[10] No particular means of implementation is implied. The important point is the identification of the processes and the intermediate products.

Figure 3 should not be interpreted as implying a monotonic progression from left to right. Every sensation does not inevitably lead to an action. It is likely that, in most tactical environments, the primary cognitive activity is situation awareness gathering (recognition, identification, inference and assessment), followed by the evaluation of potential responses.

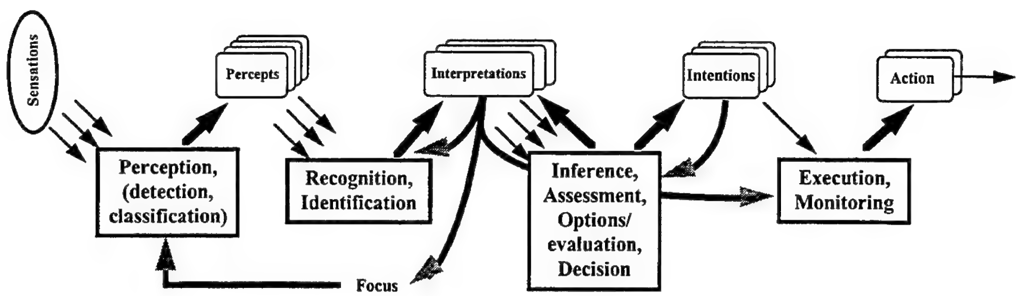

Figure 3. Tactical Response Processes

The same processes have been 'humanised' in Figure 4. Note that automatic and attentional processes have been separated and a set of regulating mechanisms (shadowed) added to force the simulation to proceed in accordance with human limitations.

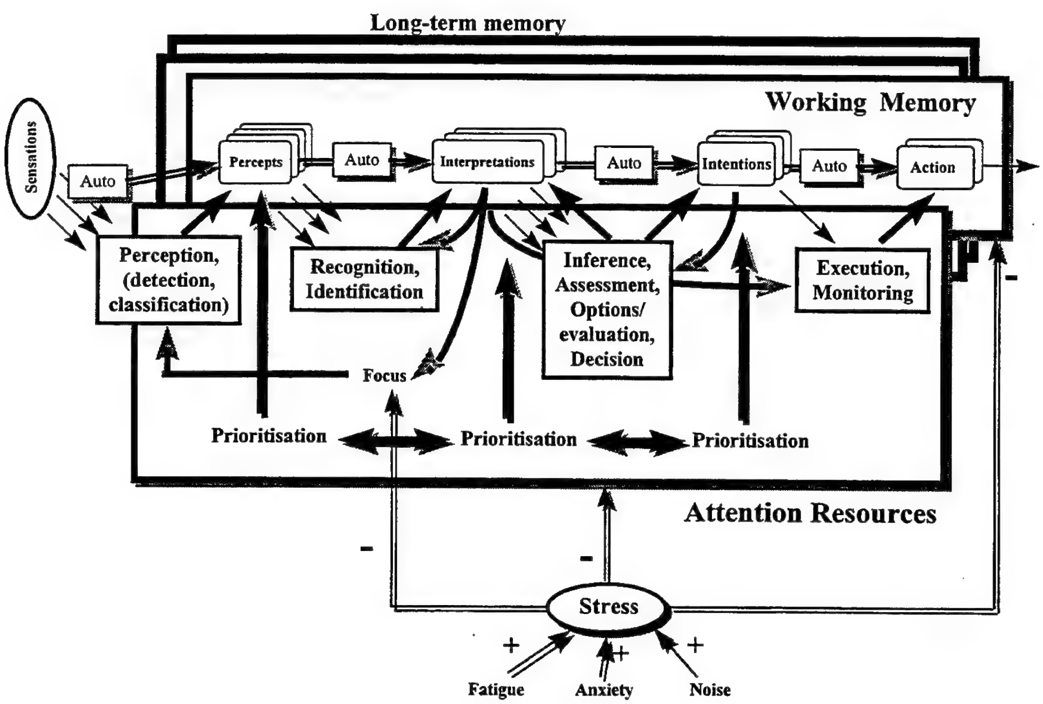

Figure 4. Regulation of Cognitive Processes

Automatic and attentional processes have been separated so that the effect of limited attentional resources and working memory can be visualised. Links to long-term memory are implied here but for simplicity, not shown. Learned patterns are available to automatic processes. Goals (or desires),procedures and semantic information in general are available to conscious processes.

The incorporation of human limitations requires two distinct stages: pre-processing[11] and run-time regulation.

Pre-processing of plans (or algorithms) prior to compilation would be required to define the automaticity of each plan as a function of the level of expertise of the human being simulated. It would be expected that, because plans, in general, will be configured in a hierarchical structure (plans call sub-plans and so on) that lower-level plans will be automatic for all levels of expertise, but that some higher-level plans will be only automatic for experts. The highest levels, eg. plans for force deployment, would never be automatic.

- The attentional loading for each component of a plan would have to be determined and stored with the plan.
- Rules for assigning the priority of each data item which could be stored in working memory must be determined and incorporated in the plan generating the item or a monitoring plan. This priority must either be a-priori, eg. missile approach warning, or context-dependent. A priority must be attached to the data item when it is generated. If the priority could change after the data item has been produced, then a plan is required to monitor the context and change the data item's priority.
- The settings for each simulated individual's attentional capacity and its response to the influence of various stressors would be stored, as would the relationship between those stressors and working memory capacity.

Run-time regulation

- will set attentional throughput capacity and focus, as well as working memory capacity dynamically, as functions of stresses on the individual.
- The items in working memory will be sorted according to priority and, contend for space. Those lower-priority items, falling outside current capacity will be displaced and 'forgotten'.
- Plans will be given priority for attentional capacity according to the priority of the data items on which they are operating. Processes with priority placing them outside current capacity will be put on 'hold' until the capacity becomes available or the data item is 'forgotten'.

Regardless of the formalism used as the basis of a simulation of human response, it should contain the essential features shown above. The detail of these models is yet to

[11] The term 'pre-processing' is not meant to imply that the process is computational. Some form of computer-aiding might be possible, but it is expected that some careful thought, aided by advice from cognitive psychologists would be required for a satisfactory result.

be developed; more research is planned as part of AOD research in support of the AEW&C capability. Approximations can be made, however, and it is important that they be provided for in the design of the simulation so that major structural changes do not have to be made later.

5. Discussion

It is possible, in principle, to organise a simulation of human tactical reasoning so that the factors limiting its progression are analogous to factors generally believed to limit real human cognition. These factors can be regulated in the simulation in the same way as the conceptualised human cognitive entities **working memory** and **attentional resources** are observed to be affected by stressors. This approach fits naturally with conventional procedural computation; working memory and attention can be regarded as analogous to memory registers and computational throughput respectively in a general purpose computer. The schemata, or patterns in long-term human memory are like computational procedures or plans, and chunks in working memory are like symbols.

A general purpose computer, however, has a fixed instruction set and the time taken by each instruction is largely determined by the hardware. The proposed cognitive process simulator has a variable instruction set. The purpose of pre-processing the plans is to establish their structure in terms of an equivalent instruction set for a simulated attentional processor. This instruction set is variable, depending on the level of skill and expertise of the simulated individual. The determination of realistic instruction times for this set, and the total capacity of the processor are real challenges. Some information is available in the literature for lower-level processes (eg. Card, Moran & Newell 1986) but more research is required to characterise higher-level processes. The development of such a human performance model is being addressed under this task (ADA 96/006 *AEW&C Support*) but useable results are not expected for several years. The important result, however, is that a structure can be established for the simulation that will not require major re-design to accommodate the human performance model.

This discussion has focussed on the impact of human characteristics on the dynamic selection and timing of procedures for processing in a simulation. Humans are also limited by the errors that they make. Some of these, briefly discussed in Appendix 1, are consistent, and can therefore be included in procedures, but other errors, such as action slips are not addressed because they are non consistent. The effect of emotion on mistakes is not considered for similar reasons. Human behaviour is conditioned by every aspect of lifetime experience, and is therefore unique. The intention, in simulating human reasoning, is to obtain responses representative of a *class* of humans, not a particular individual. If it is likely that future simulation studies will require the inclusion of these effects, eg. to test the sensitivity of standard operating procedures to mistakes, further research will be required to characterise them.

6. Conclusions

- The results of a simulated human decision, including any intermediate results, should be forthcoming in accordance with human rates of response and should be subject to typical human biases. The effects of stress and differing levels of experience and skill should be accounted for.

- Agent-oriented simulation based on the beliefs, desires, intentions (BDI) formalism has the most expressive power of readily available approaches for the simulation of human tactical behaviour and is currently in use within AOD.

- Human cognitive performance is fundamentally limited by working (short-term) memory and attentional (cognitive throughput) capacity. These are both adversely affected by stress. Automatic processes, based on familiar patterns in long term memory, are fast and require no attentional resources. Comprehension of a situation can be based on automatic recognition if the situation is familiar. The less familiar the situation, the more attention and working memory resources are required to understand it. Experts have access to richer semantic structures in long-term memory, can make more efficient use of working memory and are more likely to be able to recognise and react automatically to a tactical situation.

- The proposed approach to the inclusion of human characteristics is based on regulating access of reasoning processes (plans) to simulated cognitive resources in accordance with known human limitations. Priority of access to these resources by a plan would be based on the perceived importance of the item being reasoned about. The resources required by any plan are determined by its level of automaticity, which is in turn influenced by the expertise of the human being simulated. The automaticity of each plan (and sub-plan), and the priority of the types of data items (or symbols) being reasoned about would have to be determined a priori and stored with the plan, or determined 'on the fly' by a meta-process.

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Appendix 1: Human Cognition

Cognition, in a tactical context, is usually described in terms of problem-solving; building situation awareness, making decisions in the context of the situation as it is understood, and acting in order to bring about a desired outcome. An overview of this process, closely following that of Endsley (1989) is shown in Figure 1. 1.

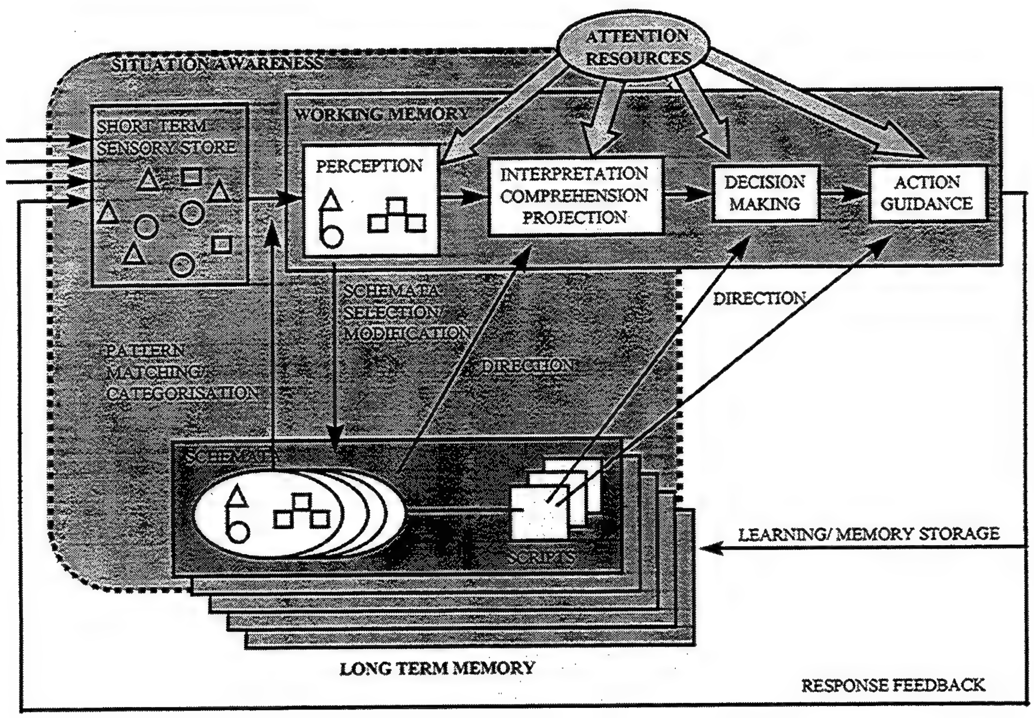

Figure 1. 1 Situation Awareness - Decision Mechanisms

The component entities and processes are discussed below.

Perception

The processes leading to perception are complex and situation-dependent. The starting point is sensing. Of the sensing modalities, only vision and audition are considered in the context of this model. Other modalities related to servomotor performance are beyond the scope of this discussion. There is evidence for both bottom-up and top-down processing in both visual and auditory modalities (Eysenck 1993, Wickens 1992).

Bottom-up, or stimulus-driven processing has a longer history of research and the results are well documented (eg. Card, Moran and Newell 1986). Top-down processes are those driven by expectation, both conscious and unconscious, based on learned patterns.
Neisser (from Eysenck 1993) proposed a perceptual cycle incorporating both bottom-up and top-down processing. The concept is illustrated in Figure 1. 2.

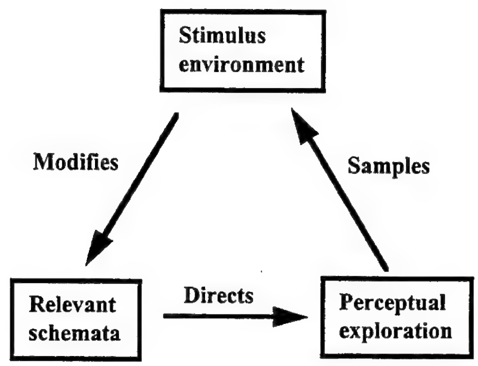

Figure 1. 2 The Perceptual Cycle

Schemata are collections of patterns or templates of knowledge derived from past experience. They provide the guidance for the recognition of images. An example of a schema is the template used for the recognition of individual letters in print. There is likely to be considerable depth of structure in all but the simplest schema. The 'letter' schemata, for example, are built on schemata for recognition of lines, and are depended upon by those used for recognition of whole words. Schemata are modified by experience. The schema for recognition of a particular letter, for example might be initially quite narrow when the printed letter is first learned in childhood, then progressively widened and as more variation in the letter is encountered.

A simple overview of the perception system is shown in Figure 1. 3, based on composite information from Eysenck 1993, Wickens 1992, Card, Moran & Newell 1986 and Endsley & Bolstad 1993.

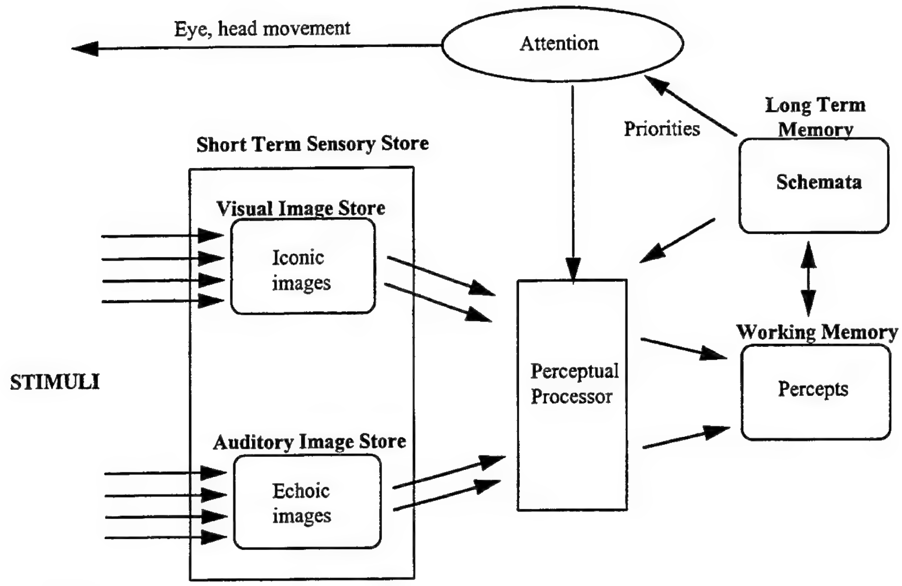

Figure 1. 3 Perception Overview

Incoming sensations are deposited in the short term sensory stores. Images in these stores have a very short half life; of the order of 100 msec for the visual store and 1 second for the auditory store. The images will fade and be lost unless the information is processed. The processing is done by reference to schemata in long term memory. The more comprehensive the schema in processing the stimulus, the more automatic and rapid the processing. Automatic, or preconscious processes require no attentional resources. The less automatic the process, the more attentional resources required. With practice, the schema is modified to cope with the expanded terms of reference and the process of perception becomes automatic.

The perceptual processor behaves as though it cycles at approximately 10 Hz (Card, Moran & Newell 1986). It exhibits characteristics consistent with both serial and 'channelised' architectures. Independent processing tasks can be performed in parallel if the total processing load is within limits and there is no cross-channel interference. This interference is at a maximum when processing similar tasks for a common sensory modality. It is generally at a minimum between different modalities, however if there is interference between similar tasks, the visual channel(s) will dominate.

Attention can be focussed in both visual and auditory modalities. The visual field of view is adjusted by head and eye movements. The auditory 'field of view' is focussed to a minor extent by head movement but, more significantly, by processing of the incoming signals to discriminate in both direction and spectral quality. Cuing by top-down processes add to the effectiveness of this discrimination.

Top-down processes contribute to perception by providing context. Presumably the perceptual processor is more efficient if it operates by reference to a more narrowly

focused set of schemata. Attentional resources can also be conserved by prioritising and focussing on cues believed to be important (eg. Fracker 1989). Motives and emotions also play a part (Wallace, Bluff & Goss 1991, Wallace, Goss & Bluff 1992).

At the second level of situation awareness, the individual builds comprehension of the meaning of the perceived information. This process is constrained by attention and working memory limitations.

The process of comprehension can be similar to the process of perception. If the situation is familiar, there being an appropriate schema available in long-term memory, recognition of the situation can be automatic , and comprehension immediate. The less familiar the situation, the more attention and working memory resources are required to achieve comprehension.

A discussion of memory resources is appropriate to provide a basis for further discussion. Note that any categorisation of memory is likely to be contentious. Although it is convenient to describe certain characteristics as belonging to different types of memory, the reality is always more complex. It is necessary, however, to make some simplifying assumptions in order to be able to model tactical thinking.

Memory can be divided into three types on the basis of observed function: Short-term Sensory Store (discussed previously), working, or short-term memory and long-term memory. Long-term memory contains most of the stored information. It is believed to be permanent and have an effectively infinite capacity (Eysenck 1993, Wickens 1992 and Card, Moran & Newell 1986). Any item in working memory, on the other hand, can be quickly displaced if it is not actively maintained.

Working Memory and Attention

Working memory can be regarded as the temporary registers, or scratch-pad of the general memory system. Half-life depends on the contents. Card, Moran & Newell (1986) give figures of approximately 7 seconds for 3 items and ten times as long for 1 item. The total effective capacity of working memory is between 5 and 9 items. This capacity is affected by environmental factors. Most significantly, its effective capacity is decreased by stress (Hockey 1986, Wickens 1992).

A model of working memory was described by Baddeley (1990). The concept is shown in Figure 1. 4.

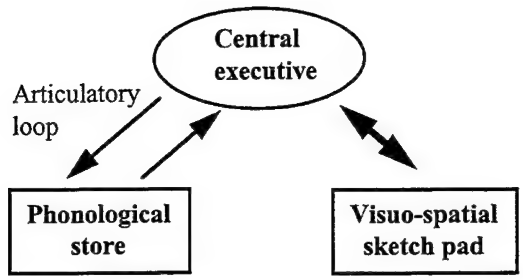

Figure 1. 4 Working Memory

The articulatory loop acts as an 'inner voice' or verbal rehearsal system. The visuo-spatial sketch pad performs the corresponding function for visual and spatial information but without rehearsal. It can be regarded as the 'mind's eye'. The central executive acts like a 'supervisory attentional system' that 'controls ongoing behaviour, maintaining goals and resisting distractions' (Colbourn 1996); it operates consciously. Eysenck (1993) regards it as 'virtually synonymous with attention'.

The limits to the function of the central executive are ill-defined. It is believed (Baddeley 1990) to play a role in comprehension. It corresponds to the 'cognitive processor' described by Card, Moran & Newell (1986) and, to some extent, to a conscious version of the perceptual processor. This processor is described as having a 'recognise-act' cycle time of between 25 and 170 msec per item, depending on the complexity of the schema, for items like colours, words and shapes.

The expressions: 'attentional resources', 'attentional capacity', 'cognitive workload' and 'mental workload' are often used in the literature in contexts that suggest that they mean the same thing. Ellis & Hunt (1993) provide some clarification in a discussion of capacity models of attention: '...we have a certain amount of cognitive capacity to devote to the various tasks confronting us. Different tasks require different amounts of this capacity, and the number of activities which can be done simultaneously is determined by the capacity each requires. If a single task demands intense concentration, no capacity will remain for an additional task. Within this approach, *attention is the process of allocating the resources or capacity to various inputs.'* This assignment of names to functions approximates the central executive function of the human working memory model to the executive function of a computer operating system.

There is more evidence for a valid analogy to be drawn between cognitive workload and computing capacity. Individual differences in comprehension ability have been specifically attributed to differences in attentional capacity (Baddeley 1990).

Frequently performed tasks, such as object recognition, tend to become automatic. The effect of automaticity is similar to that occurring earlier in the perceptual system in that

automatic tasks do not require attention and are performed without conscious awareness.

Attention is affected by stress. Not only is working memory capacity reduced, but attentional narrowing or 'tunnelling' tends to occur (Hockey 1986, Wickens et al. 1988). There is evidence that the latter effect is primarily due to prioritisation of the attended channel (Wickens 1992). This can have a negative effect if the subjective priority is incorrect due to biases in decision making. Emotional states, such as fear, can also reduce cognitive capacity (Ellis & Hunt 1993). Hockey (1986), provides a tabular summary, shown in Table 1. 1 of the observed effect of various stressors on key performance indicators.

Table 1. 1 Stress Effects on Performance

	General alertness	Selectivity of attention	Speed	Accuracy	Short-term Memory
Noise	+	+	0	-	-
Anxiety	+	+	0	-	-
Incentive	+	+	+	+	+
Stimulant Drugs	+	+	+	0	-
Later time of day	+	?	+	-	-
Heat	+	+	0	-	0
Alcohol	-	+	-	-	-
Depressant drugs	-	-	-	-	-
Fatigue	-	+	-	-	0
Sleep loss	-	-	-	-	0
Earlier time of day	-	?	-	+	+

'+' and '-' indicate an increase or decrease, respectively, in the performance indicator; '0' indicates no effect and '?' indicates insufficient data.

Anxiety reduces short-term (working) memory and increases selectivity of attention. If a perceived low level of situation awareness increases anxiety, and reduces working memory and increased selectivity of attention inhibits the building of situation awareness then there is probably an unstable feedback loop at work. This could, for example, be occurring in trainee pilots who fixate on a single instrument, and even freeze at the controls.

The effective capacity of working memory under normal conditions has been established at a mean value of 7 items. The amount of information in each of these items, or 'chunks' is variable. A chunk can be regarded as a 'set of adjacent stimulus units that are closely tied together by associations in the subject's long-term memory' (Wickens 1992). Chunking can be cumulative; chunks can be structured groupings of chunks. The limited number of items that can be held in working memory can be regarded as being pointers to chunks in long-term memory. The more information in each chunk, the more information effectively available in working memory.

Long-term Memory

Long-term memory contains all of our experience of, and beliefs about the World. It contains our knowledge, both conscious and unconscious, of how to perceive things and how to perform actions. It ultimately governs human cognition and, hence, human behaviour. Long-term memory has been classified by researchers in terms of the type of information it contains and its retrieval mechanisms. It is well understood that, whatever structures and classifications are created to describe it, the actual mechanisms of long-term memory are much more complex and inter-related. Figure 1. 5 shows a structure of memory systems and relationships to levels of consciousness based on that proposed by Tulving, and outlined by Baddeley (1990).

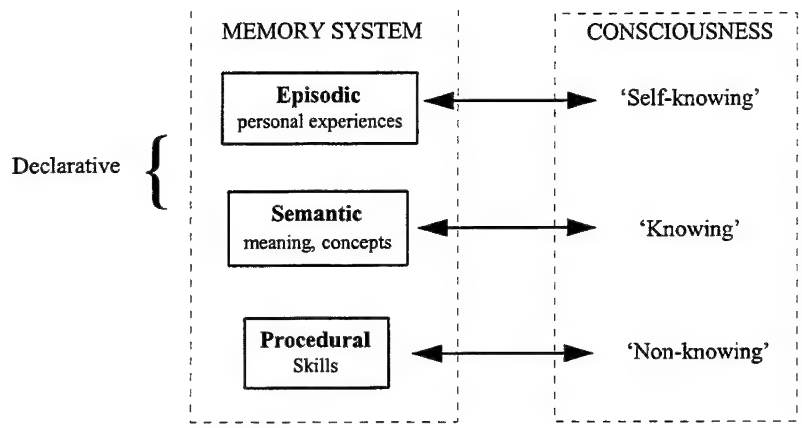

Figure 1. 5 Long-term Memory Systems

Episodic memory can be regarded, on a superficial level, as being something like a videotape of direct personal experience. It is highly likely that the experience is actually encoded and retrieved with the involvement of semantic memory. Semantic memory contains a structured representation of what the individual *understands* about the world.

Procedural memory contains information about servo-motor skills like catching a ball or riding a bicycle and well-practised cognitive skills. The contents of procedural memory would be difficult to explain in words. Servo-mechanical skills, and hence procedural memory, are outside the scope of this discussion which is seeking to provide a foundation for simulation of tactical expertise. Although such expertise depends upon a framework of automatic pattern matching the result is conscious activity; the individual would be able to explain the logic of any decision.

The process by which semantic memory is developed includes reflection on experience of the world in the context of existing semantic knowledge. This encoding process develops progressively richer structures in long-term memory. The effect of this richer

structure shows in the application of expertise. Experts are able to manipulate a lot of information in working memory because each chunk refers to a deep structure of semantic content in long-term memory. There is no need, for present purposes, to model this encoding process; there being no requirement for the simulated reasoner to 'learn'. There is a need to structure the information in simulated memory so that the mechanisms of retrieval from that memory allow human-like responses.

Long-term memory is effectively permanent memory. The major cause of forgetting from long-term memory is generally believed to be a failure in retrieval (Baddeley 1990, Ellis & Hunt 1993). Card, Moran & Newell (1986) characterise long-term memory as a slow-write, fast-read medium, with a 70 msec cognitive processing cycle for access.

Decision Making

There is an ongoing debate over the possibility of characterising human cognition sufficiently to achieve true artificial intelligence (eg. Dreyfus 1992), or of describing it within a computational framework (Penrose 1994). The aim of this discussion is relatively modest. One of the key features of true intelligence is self-evaluation and learning which is beyond the scope of this study. A truly 'intelligent' simulator would, over time, change its response to a given situation as a result of 'experience'. Repeatability is an important requirement for a simulator to be used in operations research; the requirement is for 'canned' human decision making.

One of the consistent characteristics of decision-making by experts is that they are more likely than novices to be able to recognise a situation and generate an appropriate response by pattern matching with information stored in their long-term semantic memory (Wickens 1992, Klein 1993). The expert is able to make use of understanding based on the integration of experience into a richer semantic network than the novice. The expert can call upon larger, more appropriately structured 'chunks' of information with which to match the currently perceived situation. The expert is more likely to be able to make a decision with minimum use of working memory and attention, while the novice will have to use both of these resources to make sense of the situation and generate a response.

A familiar situation might be recognised and responded to almost automatically, while an unfamiliar situation, or an unfamiliar requirement for a response can make significant demands on working memory and attentional resources.

The meaning of 'recognition' and 'decision' can vary considerably in complexity, depending on the situation. If, for example, the percept is the illumination of a particular light in a cockpit, and there is only one appropriate response, the recognition-decision-action process could be trivial. In a situation rich in context and involving multiple percepts, even the meaning of 'recognition' is likely to be difficult to define.

An influential view of the factors contributing to the recognition-decision process is available. Klein (1993) and the Naturalistic Decision Making (NDM) school argue that human decision making in natural environments is situation-dependent. Much of the research on NDM is focussed on elicitation and analysis of the cues actually used by experts and the design of the workplace to maximise its ability to support the decision maker.

Humans, particularly experts, make use of a rich framework of context and cues to recognise a situation and decide on a response without comparing options. This process is known as a Recognition Primed Decision (RPD). Klein describes the factors contributing to a RPD: goals that make sense so that 'foolish' responses are not considered; selectivity in only using relevant cues; expectations that accurately reflect the unique features of a situation and knowledge of appropriate responses. Klein represents a simple RPD diagrammatically in Figure 1. 6.

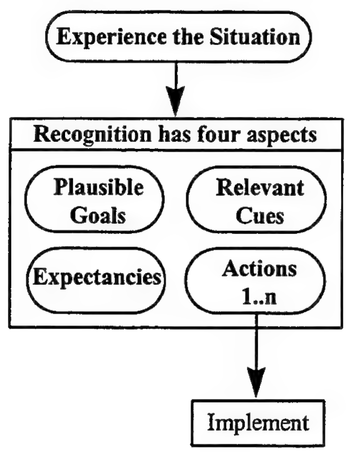

Figure 1. 6 Simple Match

A model of a more complex recognition-decision strategy, based on Klein's is shown in Figure 1. 7.

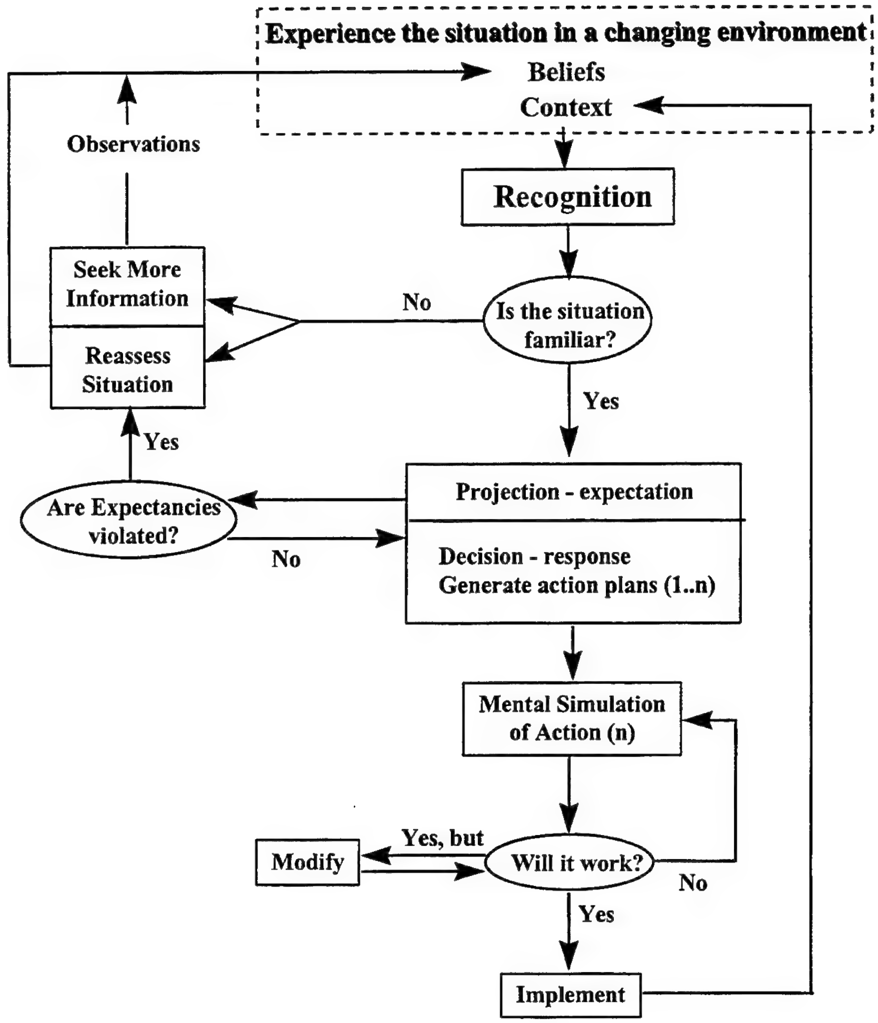

Figure 1. 7 Recognition - decision Strategy

Although this is intended to be a representation of the way humans approach a problem, it provides a useful top-level overview of the process as a guide for design of a simulation of human thinking. The complexity of each block would depend on the intended level of detail of the simulation and the role of the human being simulated. A severely time-critical role, such as a fighter pilot, would involve an absolute minimum of evaluation of options by mental rehearsal. A commander, on the other hand, is much more likely to attempt to optimise a response by evaluating alternative courses of action. The availability of staff advice and computer-based decision-support aids will further complicate the model.

An approach to the process, consistent with NDM, is to store actual human decisions elicited on presentation of each unique set of context and cues. This has an obvious attraction for necessarily simple situations but presents some challenges for more

complex ones. Given that each dimension of the situation could be parameterised, a decision-action would have to be elicited and encoded for each combination of parameters. Creative design of the knowledge base would be required to eliminate redundancy. The processes in Figure 1. 7 require manipulation of the contents of the knowledge base at a semantic level especially when re-casting of the situation is required and the context is changed. Comparison and evaluation of options is required. Human biases in perception and assessment should be taken into account when modelling these processes.

Wickens and Flach (1988) offer a model of decision-making biases and heuristics, shown in Figure 1. 8.

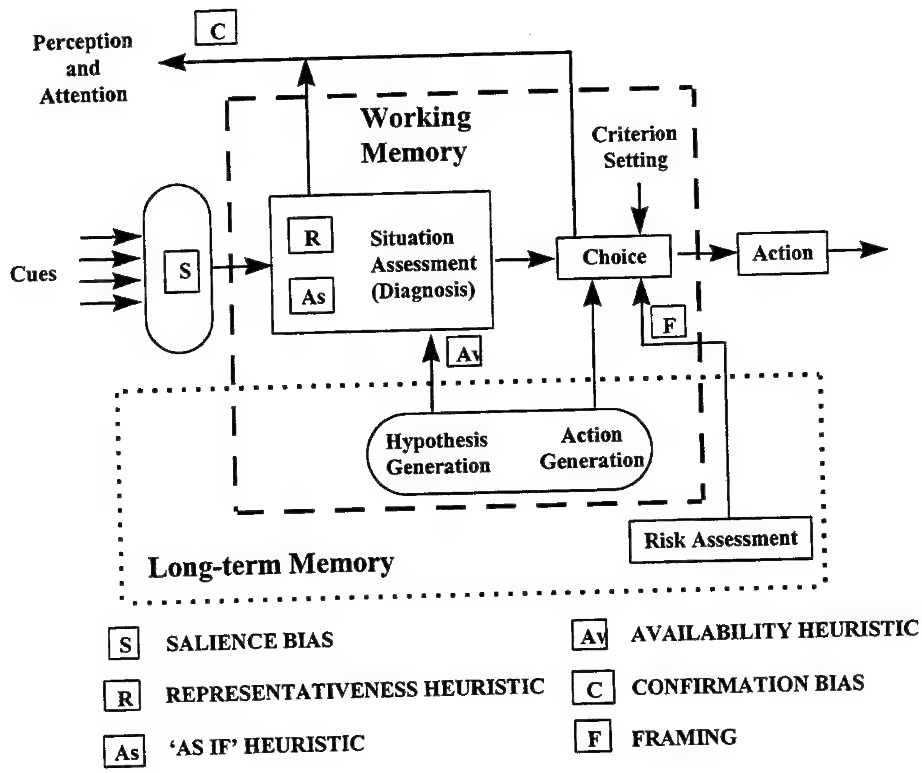

Figure 1. 8 Decision Making Biases and Heuristics

Salience bias is the tendency for perception to be dominated by the most obviously presented information, particularly in the visual modality.

Confirmation bias is the tendency to look for cues that tend to support the hypothesis already believed to be true (however tentatively), while the best hypothesis-testing strategy is to seek cues that would prove it to be untrue.

The **representativeness heuristic** is the tendency to try to match the set of cues seen with a single typical or representative pattern for the hypothesised situation. The observed pattern may not be sufficiently diagnostic, ie. it may be consistent with a number of other possible (untested) hypotheses. A rational strategy would be to generate a set of hypotheses to cover the range of possibilities and evaluate each one against the available evidence.

The **availability heuristic** is the tendency to consider the hypothesis which springs most readily to mind as the most likely. This could be a problem when the situation corresponding to the hypothesis was the last one experienced, or the easiest to remember.

The **'as if' heuristic** is the tendency to treat all sources of information as though they were of equal value. The optimal strategy would be to weight the data according to its reliability.

Framing bias is a failure to fully consider and accurately weight the risks and benefits in the decision being made.

It is clear that, even though these potential errors are couched in terms consistent with evaluating hypotheses against the evidence, they must also affect recognition-primed decisions. In many operational settings, the limitations of attentional resources and working memory would, in any case, tend to preclude evaluation of multiple options, especially with time pressure and the demands of other tasks. Decision makers, especially experts, implicitly recognise this and adopt the appropriate strategy. Klein (1993) offers a table of 'boundary conditions' for decision strategies, reproduced in Table 1. 2 Boundary Conditions for Decision Strategy Options.

Table 1. 2 Boundary Conditions for Decision Strategy Options

	Singular	Comparative
Time Pressure	x	
Experience Level	x	
Dynamic Conditions	x	
Ill-defined Goals	x	
Justification		x
Conflict Resolution		x
Optimisation		x
Computational Complexity		x

Although it is reasonable to expect that experience makes an expert more likely than a novice to be able to make an immediate decision, and get it right, the assumption is not always valid. Experts are subject to the biases and use of heuristics shown above, and more. Wickens (1992) lists biases that can distort the acquisition of expertise by experience. Misleading feedback may occur if a correct decision yields an incorrect outcome because of chance factors, or if a correct outcome occurs for the wrong

reasons. Delayed feedback may cause the factors influencing the decision to be forgotten or distorted by time. Feedback may be selectively perceived. These biases are built into semantic memory and, if they are to be modelled, should be reflected in the stored knowledge base.

Action Guidance

An action can be as simple as changing a belief which, if held in working memory, is instantaneous. It can be a complex sequence of moves which have to be monitored in progress and continually re-evaluated in a changing environment. In this case, the intended action becomes part of the 'plausible goals' and 'expectations' in the situation assessments in the future. It should be borne in mind that the maintenance of these goals and expectations will use working memory and attentional resources. The loading of these resources will be reduced by prior experience of similar situations, and hence access to chunks of relevant information based on long-term semantic memory.

Cognitive resources

All theories of human cognition have some important features in common. Some processes are automatic, ie. they do not use attention resources or working memory, other than the 'chunk' of information resulting from the process. Where the process is not automatic, cognitive resources are used, and those cognitive resources are limited. Attention and working memory; the resources used for 'thinking', are both adversely affected by various forms of stress. The rate and effectiveness of 'thinking' depend on these factors, and the level of ability and experience of the thinker. Any simulation of human cognition should include a mechanism to regulate access to resources.

Regardless of the formalism used as the basis of a simulation of human response, it should contain the essential features shown above. The execution of a learned skill, eg. catching a ball, would proceed as a totally automatic process based on matching of learned semantic patterns in long-term memory. It would start with the sensation of seeing the ball, automatic recognition and projection of its trajectory, intention to catch it and production of the responses to intercept and grasp it. There would, of course, be several iterations in the tracking and intercepting procedure. Cognitive resources would be loaded to the extent that there would be conscious awareness of the ball; a chunk in working memory, but attention would hardly be disturbed.

If, at any stage, the automatic process does not 'fire', attentional resources may be called into play, subject to availability and perceived priority. A simulation should include a method of metering attention resources (cognitive processing capacity) and assigning priority to semantic chunks generated by those processes (and automatic processes), including the feedback effect on attention of perceived priority. The chunks outside the current capacity of working memory would be displaced and lost.

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19. ABSTRACT

The effect of errors in models of human response on the outcome of a simulated sequence of events can be significantly large compared to the precision with which physical events are typically modelled. The effects of such errors can accumulate when events are propagated up and down a command and control chain. For a simulation of a system to be realistic, the products of simulated human decisions should be available in accordance with human cognitive limitations and at human rates of response.

An approach to structuring simulations of human tactical response is proposed. This approach requires pre-processing of the simulation procedures to establish their cognitive resource loading for different levels of simulated expertise. Run-time processes are also required to regulate access of behaviour algorithms to simulated cognitive resources, and to dynamically adjust those resources as a function of stress.